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(71) Applicant: AM INTERNATIONAL INCORPORATED
333 West Wacker Drive Suite 900
Chicago Illinois 60606-1265(US)

(72) Inventor: Bartky, Walter Scott
5445 N. Sheridan Road
Chicago, Illinois 60640(US)
Inventor: Paton, Anthony David
The Thatched Cottage, 51 Mills Lane
Cambridge(GB)

(74) Representative: Coleman, Stanley et al
MATHYS & SQUIRE 10 Fleet Street
London EC4Y 1AY(GB)

(54) Method of testing components of pulsed droplet deposition apparatus.

(57) A method for testing body components of pulsed droplet deposition apparatus comprises applying a variable frequency voltage to the electrodes of each of a number of selected channel wall elements (24). The resulting impedance variations are used to determine the natural frequencies of the selected wall elements which, in turn, are used to determine whether the compliance ratios of the selected wall elements and the droplet liquid to be used therewith lies within a desired range of values.

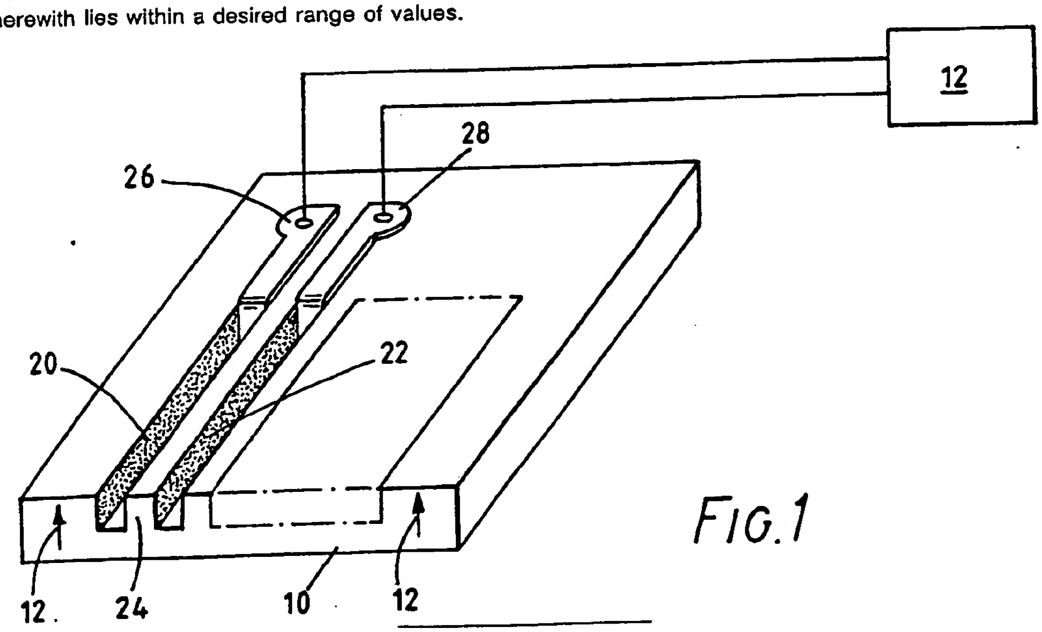

FIG.1

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Method of Testing Components of Pulsed Droplet Deposition Apparatus

This invention relates to a method of testing body components of pulsed droplet deposition apparatus having a body formed with an array of parallel channels having channel dividing walls formed by piezo-electric material, nozzles communicating with said channels and droplet deposition liquid supply means connected to said channels. The body components with which this invention is particularly concerned each comprise a sheet formed with a multiplicity of parallel channels having upstanding channel dividing side wall elements formed from, piezoelectric material poled in a direction normal to said sheet and plated each on opposite channel facing wall surfaces thereof with electrodes. Such body components of pulsed droplet deposition apparatus are referred to herein as body components "of the kind set forth".

Pulsed droplet deposition apparatus having bodies formed from body components of the kind set forth are described in European patent Applications Nos. 88300144.8 and 88300146.3, the contents of which are herein incorporated by reference. In these European patent applications there are described various forms of pulsed droplet deposition apparatus one of which employs a body component of the kind set forth and a further body component comprising a sheet of inactive material bonded to the free ends of the channel dividing side walls to form the channel array the channels of which are of rectangular transverse cross-section. Accordingly, in this form of channel array body, the channel dividing side walls form monolithic cantilever actuators which are displaceable by electrical impulses applied to their electrodes to impart to droplet liquid in the channels pressure impulses for effecting droplet ejection from the channels which takes place through nozzles which in the operative droplet deposition apparatus communicate with the respective channels of the array.

In another form of droplet deposition apparatus described in the European patent applications referred to there are employed two body components of the kind set forth, the channel dividing side walls of which are bonded together at the free ends thereof to form the channel array of channels of rectangular crossection.

In this form of channel array a voltage impulse applied to the electrodes of the channel dividing side walls deflect said side walls in shear mode into chevron formation so imparting to droplet liquid in the channels into which said channel dividing side walls are deflected pressure pulses for ejection of droplets from the respective channels of the array.

In both of the forms of pulsed droplet deposition apparatus, which in practice are drop-on-demand ink jet printers, the channel dividing wall actuators may serve the channels on opposite sides thereof, that is to say each is deflected in opposite senses to effect droplet ejection from the respective channels on opposite sides thereof.

It will be apparent accordingly that body components of the kind set forth are vital components of the kinds of pulsed droplet deposition apparatus described. It is important therefore that a procedure for reliably testing such body components in the initial stages of the manufacturing process be available so that early rejection of imperfect specimens can take place. It is a principal object of the present invention to afford such a procedure.

An important design parameter utilised in the development of drop-on-demand printheads employing shared wall actuators such as are described in European patent application No. 88300146.3 is that of compliance ratio (CR). This quantity is the ratio of the compliance of each channel dividing wall actuators to that of the ink in the ink channels of the array. Thus $CR = C_W/C_I$. This value has been found to influence:-

(a) the velocity of sound at which the acoustic waves giving rise to droplet ejection travel in the ink in the ink channels;

(b) the degree of pressure cross-talk - i.e. the effect on the ink pressure in one actuated channel of a neighbouring channel or channels being actuated at the same time - between neighbouring actuated channels of the same group of channels, the channels of a drop-on-demand printhead employing shared channel dividing wall actuators being arranged in at least two groups of interleaved channels, selected channels of each group being actuated group by group in sequence; and

(c) the coupling efficiency between the voltage applied to the electrodes of an actuator and the velocity of an ejected ink droplet.

If a value of CR close to zero is adopted, so that the actuator walls are virtually rigid, the velocity of sound is ostensibly that in the ink alone, and the cross-talk coupled into the neighbouring channel in the same group is negligible. Despite these simplifications such a design is unattractive because it requires high values of wall and channel width in the array direction, that is to say the direction normal to the channel axes and in the plane thereof. As a consequence relatively high actuating voltages are called for and the channel density is limited.

It has been found that compliance ratios in the range $0.3 \leq CR \leq 3$ give satisfactory results with optimum results being achieved in the range $0.5 \leq CR \leq 0.67$. Values in this latter range give the most efficient coupling between applied voltage and drop velocity, independent of the scale of the printhead, i.e. the number of channels per millimetre which in high density arrays is greater than two. The preferred value in the range depends on whether all channels or only one channel of a group are actuated at the same time. At such values modal interaction, the cause of cross-talk, between ink channels occurs so that the actuating voltage to produce an ejected drop of given size and velocity is dependent on the print pattern.

It has also been deduced that a relationship exists between compliance ratio and the natural frequency of the actuator channel dividing walls which provides the basis for the method of testing body components according to the invention. This relationship is arrived at by employing Rayliegh's approximation which infers that any estimate of the natural frequency of a uniform beam - in the present case, the beams provided by the channel wall actuators - if the modal shape is unknown, can be obtained by assuming a suitable shape such as the static deflection of the beam under uniform pressure. The relationship deduced is

$$CR = \frac{1}{K} \cdot \frac{1}{4\pi^2} \cdot \frac{B}{wb\rho} \cdot \frac{1}{f^2}$$

where K is a constant, typically equal to 1.5

B is the bulk modulus of the ink

b is the mean width of the ink channel (i.e the channel cross-sectional area ÷ the channel wall height)

w is the channel wall width

ρ is the mean density of the channel wall

f is the natural frequency Using the value 1.5 for K, the relationship becomes

$$CR = \frac{1}{60f^2} \frac{B}{b\rho w}$$

or

$$f = \sqrt{\frac{1}{60CR} \frac{B}{b\rho w}} \qquad \text{——— } 1$$

For $.5 \leq CR \leq .67$ this gives:-

$$0.158\sqrt{\frac{B}{b\rho w}} \leq f_1 \leq 0.183\sqrt{\frac{B}{w\rho b}}$$

where f_1 is the natural frequency of the wall actuator after bonding. This can be written as follows:

$$0.158\sqrt{\frac{B}{wb\rho}}\ \frac{f_o}{f_1} \leq f_o \leq 0.183\sqrt{\frac{B}{w\rho b}}\ \frac{f_o}{f_1} \qquad \text{——— } 2$$

where f_o is the natural frequency of the wall actuator prior to bonding.

For $0.3 \leq CR \leq 3$ equation 2 can be restated to provide a wider range of acceptable values of f_o.

The compliance ratio of an assembled i.e. a bonded, actuator can therefore be obtained from equation 1 i.e. from its natural frequency f, and from the properties B, b of the ink and ink channel together with the properties W,o of the actuator wall. A prediction of the compliance ratio can be obtained before the actuator is bonded to form the channel array by measuring the natural frequency, fo, of the actuator wall after plating the electrodes thereon but before bonding.

Given a knowledge of f_o/f_1, a component is checked as being satisfactory for use provided f_o for all of

the measured wall actuators lies within the range given by equation 2 or the wider range of f_o given by equation 2 for $0.3 \leq CR \leq 3$. A knowledge of f_o/f_1 can be obtained from geometrical considerations as described hereinafter or from accumulated experience of measuring f_o before and f_1 after bonding.

The method of testing body components of the kind set forth, according to the present invention is characterised by applying to each of said body components a variable frequency voltage at said electrodes of each of a number of selected wall elements thereof to determine, from impedance variations in each of said selected wall elements, the natural frequency thereof, evaluating from the natural frequency of each of said selected wall elements a comparison of the values of the wall compliances and whether the compliance ratio of each of said selected wall elements and droplet liquid to be employed in said pulsed droplet deposition apparatus lies within a desired range of values and accepting for production of bodies of said apparatus said body components of which said selected wall elements have respective compliance ratios with said droplet liquid lying within said desired range of values.

Preferably, the method of the invention is characterised by applying a variable frequency voltage to said electrodes of each of said side wall elements to determine from impedance variations in each of said side wall elements, the natural frequency thereof, evaluating from the natural frequency of each of said side wall elements whether the compliance ratio of each of said side wall elements and droplet liquid to be employed in said pulsed droplet deposition apparatus lies within a desired range of values and accepting for production of bodies of said apparatus said body components of which said side wall elements have respective compliance ratios with said droplet liquid lying within said desired range of values.

The method of the invention thus far identifies those components tested which are suitable to go forward to the next stage of production. The specimens which are adjudged suitable can then go forward for bonding thereto of a further member, which can be a sheet of inactive material or another like tested component, and then further testing by applying said variable frequency voltage to the electrodes of each of said wall elements to which said voltage was applied prior to said bonding to determine from impedance variations of each of said wall elements subject to said voltage the natural frequency thereof and evaluating from the natural frequency of each of said wall elements determined after bonding thereto of said further member whether the compliance ratio thereof and of said droplet liquid lies within said desired range of values.

Suitably the desired range of values is given by $0.3 \leq CR \leq 3$ and within that range the preferred range is $0.5 \leq CR \leq 0.67$.

The invention will now be described, by way of example, with reference to the accompanying diagrammatic drawings, in which:

FIGURE 1 illustrates a body component of a pulsed droplet deposition apparatus, suitably, a high density array, drop-on-demand, ink-jet printer under test according to the invention; and,

FIGURE 2 is a sectional view of two like components after testing and prior to bonding together of the channel dividing walls thereof to form part of the channel array of the printhead of the printer.

Figure 1 shows a body component 10 formed from piezo-electric material, suitably PZT, poled in a direction normal to the sheet, indicated by the arrows 12. Although the component 10 is shown as a monolithic piece of piezo-electric material, it may instead be a laminate of a sheet of piezo-electric material and a substrate of inactive material. An array of parallel channels 20,22 is formed in the piezo-electric material which, where a laminate is used, may extend through the piezo-electric layer and partially into the inactive substrate. Between each pair of channels 20,22 is thus provided an upstanding channel dividing wall 24 and this is plated on opposite channel facing surfaces thereof with conductive material to provide electrodes to which a voltage can be applied to deflect the wall 24 in shear mode. The plated electrodes are connected to contact pads 26,28 which are themselves connected to a phase analyser 12, for example an HP4194A manufactured by the Hewlett Packard Company of the United States of America. This instrument is employed to apply to selected or each of the walls 24 in turn a sweep frequency from which the impedance at resonance and anti-resonance is measured. Alternatively, the pads 26 and 28 are connected in an impedance bridge supplied with a variable frequency.

The fundamental resonance of the wall is accordingly stimulated and detected at frequency f_o by the analyser 12 or the alternatively used impedance bridge. Since the wall 24 is free at its upper end the measured resonant frequency of the wall is the resonant frequency in cantilever mode.

The component 10 can be employed with a sheet of inactive material (not shown) bonded to the free ends of the walls 24 to provide an array of channels of rectangular transverse cross-section of which the dividing walls are cantilever actuators, or can be bonded, as indicated in Figure 2 to a like component to provide an array of channels of rectangular transverse cross-section of which the dividing walls comprises actuators which are deflectable into chevron-like form.

In the case of a chevron type actuator, the component 10 may be bonded to a like component by a

bond layer which is relatively compliant so that the upper walls 24 are bonded to the lower walls 24 effectively with a pin joint characteristic, which couples these walls in shear, but not in bending. The resonant frequency of the assembled printhead body part is then $f_1 = f_o$. In order to ensure that the compliance ratio will be correct after assembly a resonance check f_o is first performed on both components 10 for the walls 24 of the range.

$$0.158\sqrt{\frac{B}{wb\rho}} \le f_o \le 0.183\sqrt{\frac{B}{wb\rho}}$$

After bonding, if the resonant frequency of walls 24 is remeasured the same value should be obtained.

If the chevron bond layer is a rigid bond so that the bond inhibits rotation as well as shear, then the cantilever mode f_o of resonance prior to bonding becomes that of a built-in beam of resonance f_1 and

$$\frac{f_1}{f_o} = 1.59$$

(the derivation of this value is referred to below)
so that f_1 must have frequencies greater than f_o in the ratio 1.59 to obtain the correct compliance ratio when bonded.

Similarly in the case of the monolithic cantilever actuator if the free cantilever is bonded by in effect a pin jointed end, bonding alters the resonant frequencies by

$$\frac{f_1}{f_o} = 4.37$$

(the derivation of this value is referred to below) so that f_o and f_1 can be similarly tracked to keep CR of the finished actuator at the design value after assembly.
For a rigid bond in the cantilever actuator form

$$\frac{f_1}{f_o} = 6.36.$$

The ratio

$$\frac{f_1}{f_o} = 1$$

or 1.59 for the chevron actuator with a pin jointed or rigid bond and the values

$$\frac{f_1}{f_o}$$

of 4.37 or 6.35 in the pin jointed and rigid bond cases of the cantilever actuator are derived from a table "7.3 Natural Frequencies and Normal Modes of Uniform Beams" of values which appears at page 7-14 of Volume I of the text book "Shock and Vibration Handbook" edited by Cyril M Harris and Charles E. Crede.

In the table referred to it will be seen from column (E) that the frequency f_0 is proportional to k^2 for an unclamped cantilever which is a proportion of $(1.875)^2$ whilst f_1 for the chevron type actuator with a rigid bond is the same proportion of the square of half of the clamped-clamped value of k which is 4.730 so that

$$\frac{f_1}{f_0} = \frac{(4.730/2)^2}{(1.875)^2} = 1.59$$

The reason for taking one half of the clamped-clamped value of k is that with the chevron arrangement the length of the free cantilever beam is half that of the clamped-clamped beam.

Similarly, in the case of the cantilever arrangement the values of k for the pin jointed bond are taken from the clamped-hinged beam and the unclamped cantilever beam values so that

$$\frac{f_1}{f_0} = \frac{(3.927)^2}{(1.875)^2} = 4.37$$

whilst for the rigid bond, the values of k are taken from the clamped-clamped beam and the unclamped cantilever beam values, so that

$$\frac{f_1}{f_0} = \frac{(4.730)^2}{(1.875)^2}$$

In the case of all the tests referred to, in addition to determining that the natural frequency, both before and after the bonding process, of each of the channel side walls tested lies within the specified range of values, it is further ascertained, as is normal in a test procedure of this general kind, that the natural frequencies of the walls tested, in each of the tests made prior to and after the bonding stage, are closely similar to one another.

Claims

1. The method of testing body components of pulsed droplet deposition apparatus having a body formed with an array of parallel channels, nozzles respectively communicating with said channels and droplet liquid supply means connected to said channels, said body components each comprising a sheet formed with a multiplicity of parallel channels having upstanding parallel channel dividing side wall elements formed from piezo-electric material poled in a direction normal to said sheet and plated each on opposite, channel facing wall surfaces thereof with electrodes, said method being characterised by applying to each of said body components a variable frequency voltage at said electrodes of each of a number of selected wall elements thereof to determine, from impedance variations in each of said selected wall elements, the natural frequency thereof, evaluating from the natural frequency of each of said selected wall elements a comparison of the values of the wall compliances and whether the compliance ratio of each of said selected wall elements and droplet liquid to be employed in said pulsed droplet deposition apparatus lies within a desired range of values and accepting for production of bodies of said apparatus said body components of which said selected wall elements have respective compliance ratios with said droplet liquid lying within said desired range of values.

2. The method claimed in Claim 1, characterised by applying a variable frequency voltage to said electrodes of each of said side wall elements to determine from impedance variations in each of said side wall elements, the natural frequency thereof, evaluating from the natural frequency of each of said side wall

elements whether the compliance ratio of each of said side wall elements and droplet liquid to be employed in said pulsed droplet deposition apparatus lies within a desired range of values and accepting for production of bodies of said apparatus said body components of which said side wall elements have respective compliance ratios with said droplet liquid lying within said desired range of values.

3. The method claimed in Claim 1 or Claim 2, characterised by bonding to the channel dividing side wall elements of each of said accepted body components a further member to form part of said array of parallel channels, applying said variable frequency voltage to the electrodes of each of said wall elements to which said voltage was applied prior to said bonding to determine from impedance variations of each of said wall elements subject to said voltage the natural frequency thereof and evaluating from the natural frequency of each of said wall elements determined after bonding thereto of said further member whether the compliance ratio thereof and of said droplet liquid lies within said desired range of values.

4. The method claimed in any preceding claim, characterised by employing the range 0.3 $\leq CR \leq$ 3 as the desired compliance ratio range of values.

5. The method claimed in any one of Claims 1 to 3, characterised by employing the range 0.5 $\leq CR \leq$ 0.67 as the desired compliance ratio range of values.

6. The method claimed in Claim 1 or Claim 2, characterised by bonding together said side wall elements of two like body components accepted for production of bodies of said apparatus to form a body having an array of parallel channels, applying said variable frequency voltage to the electrodes of each of said wall elements of each of said like body components to which said voltage was applied prior to bonding together of said components to determine from impedance variations of each of said wall elements subject to said voltage the natural frequency thereof and evaluating from the natural frequency of each of said wall elements determined after bonding of said components whether the compliance ratio of each of said components and droplet liquid lies within a desired range of values.

7. The method claimed in Claim 6, characterised by employing the range 0.3 $\leq CR \leq$ 3 as the range of desired values of compliance ratio.

8. The method claimed in Claim 6, characterised by employing the range 0.5 $\leq CR \leq$ 0.67 as the range of desired values of compliance ratio.

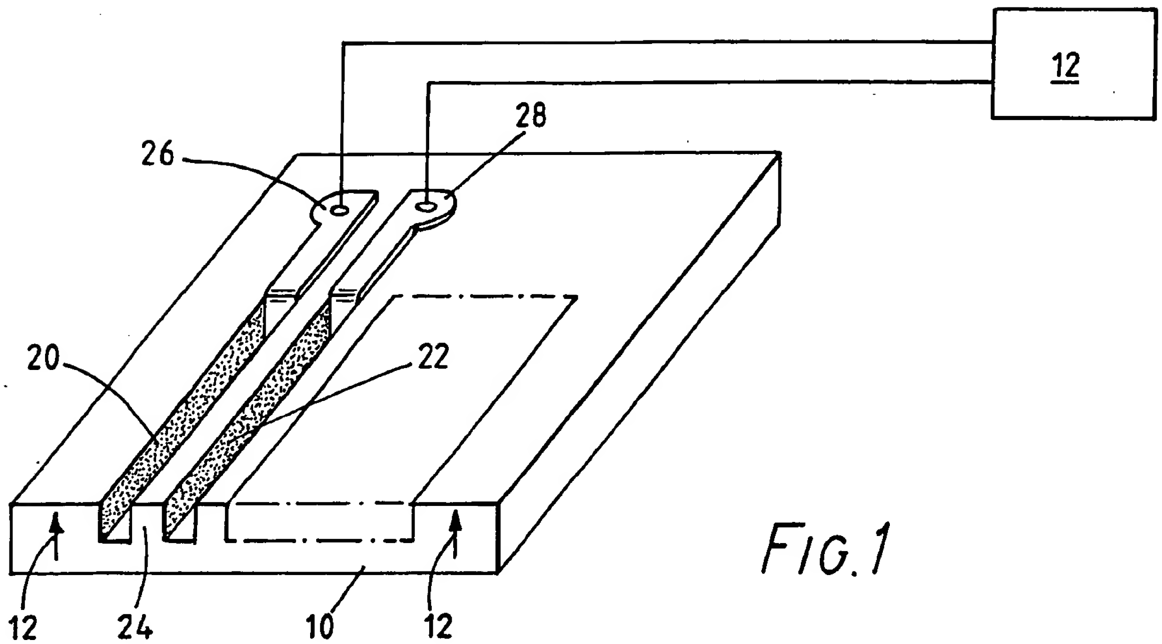

FIG.1

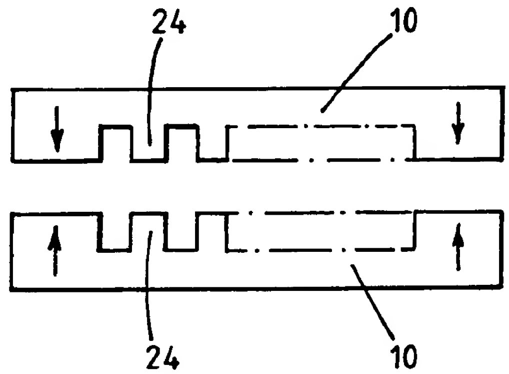

FIG.2

European Patent Office

EUROPEAN SEARCH REPORT

Application number

EP 89313355.3

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.⁵)
D,A	EP - A1 - 0 278 590 (AM INTERNATIONAL INCORPORATED) * Totality *	1	B 41 J 2/045
A	EP - A1 - 0 116 971 (SIEMENS) * Totality *	1	
A	EP - A1 - 0 273 282 (AMERICAN TELEPHONE AND TELEGRAPH COMP.)		
A	DE - A1 - 3 129 015 (SIEMENS)		

TECHNICAL FIELDS SEARCHED (Int Cl.⁵)

B 41 J
G 01 D
H 01 L

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
VIENNA	02-04-1990	WITTMANN

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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